Mon. Not. R. Astron. Soc. **360,** 1257–1261 (2005) doi:10.1111/j.1365-2966.2005.09100.x

Bipolar jet growth and decline in Hen 3-1341: a direct link to fast wind and outburst evolution★

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Accepted 2005 April 7. Received 2005 March 19; in original form 2005 January 29

ABSTRACT

We report on and investigate the evolution and disappearance in the symbiotic star Hen 3-1341 of collimated bipolar jets, which take the form of symmetrically displaced components of emission lines. From modelling of the emission-line spectrum it turns out that the accreting white dwarf (WD) in quiescence has $T_{\rm WD} \sim 1.2 \times 10^5$ K and $R_{\rm WD} \sim 0.14\,{\rm R}_\odot$, for a luminosity of 3.8×10^3 L$_\odot$, and it is stably burning hydrogen on the surface at a rate of $\dot{M}_{\rm H} \sim 5 \times 10^{-8} {\rm M}_\odot$ yr^{-1}, feeding ionizing photons to a radiation bounded circumstellar nebula extending for ∼17 au. The WD underwent a multimaxima outburst lasting from 1998 to 2004 during which its H-burning envelope reacted to a probable small increase in the mass accretion by expanding and cooling to $T_{\rm eff} \sim 1 \times 10^4$ K and $R \sim 20\,{\rm R}_\odot$, mimicking an A-type giant that radiated a total of $\sim 6 \times 10^{44}$ erg, at an average rate of $\sim 1 \times 10^3$ L$_\odot$. Bipolar jets developed at the time of outburst maximum and their strength declined in parallel with the demise of the fast wind from the inflated WD, finally disappearing when the wind stopped halfway to quiescence, marking a 1:1 correspondence between jets presence and feeding action of the fast wind. The total mass in the jets was $M_{\rm jet} \sim 2.5 \times 10^{-7}\,{\rm M}_\odot$ for a kinetic energy of $E^{\rm kin}_{\rm jet} \sim 1.7 \times 10^{42}$ $(\sin i)^{-1}$ erg, corresponding to $\sim 0.3(\sin i)^{-1}$ per cent of the energy radiated during the whole outburst. We suggest that the spectroscopic search for jets in symbiotic stars could pay higher dividends if focused on the outburst phases characterized by maximum wind intensity.

Key words: binaries: symbiotic – stars: mass-loss – stars: winds, outflows – ISM: jets and outflows.

1 INTRODUCTION

Tomov, Munari & Marrese (2000, hereafter TMM) discovered spectroscopically in Hen 3-1341 (=V2523 Oph) one of the finest examples of highly collimated bipolar jets seen in a symbiotic binary. The jets, with a projected velocity of $|\Delta R\,{\rm V}_\odot| \sim 820$ km s^{-1}, were observed when the system was in outburst at $V \sim 10.5$ mag. No follow-up study monitored the jet or outburst evolution.

Some symbiotic binaries are already known to present or have presented jets, in the optical, radio and/or X-rays: R Aqr (Burgarella & Paresce 1992; Dougherty et al. 1995; Kellogg, Pedelty & Lyon 2001), CH Cyg (Taylor, Seaquist & Mattei 1986; Solf 1987; Crocker et al. 2002; Galloway & Sokoloski 2004), MWC 560 (Tomov et al. 1990; Shore, Aufdenberg & Michalitsianos 1994; Schmid et al. 2001), RS Oph (Taylor et al. 1989), Hen 2-104 (Corradi et al. 2001) and Hen 3-1341 (TMM). Other possible examples of jets or collimated mass outflows from symbiotic binaries and related systems are StHα 190 (Munari et al. 2001), Z And (Brocksopp et al. 2004), AG Dra (Mikolajewska 2002), V1329 Cyg and HD 149427 (Brocksopp, Bode & Eyres 2003).

It is not an easy task to correlate in symbiotic stars the appearance of jets with the system properties. In fact, the ionized circumstellar gas is so bright in the optical and ultraviolet as to prevent direct observation of the central engine, which is believed to be an accreting white dwarf (WD) that in many cases experiences quasi-stable surface H-burning (Munari & Buson 1994; Sokoloski 2003). The standard scenario for the production of jets (e.g. Livio 1997) involves an accretion disc which is threaded by a vertical magnetic field and an energy/wind source associated with the central accreting object. A widespread presence of accretion discs and magnetic fields in symbiotic binaries is still a matter of debate. Convincing detection of a magnetic field in a symbiotic binary has so far been obtained only for Z And (Sokoloski & Bildsten 1999), in the form of a persistent ⩽0.005 mag amplitude oscillation at 28-min period interpreted as the spin period of a magnetic WD. The detection was made possible by the outburst state of Z And at the time of

★Based in part on observations secured at the Observatoire de Haute-Provence within the OPTICON 2004 access programme.
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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Bipolar Jet Growth and Decline in Hen 3-1341: A Direct Link to Fast Wind and Outburst Evolution**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Naval Observatory 3450 Massachusetts Avenue, N.W. Washington, D.C. 20392-5420**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Table 1. The table collects existing and new multiband information on the photometric history of Hen 3-1341. Sources are as follows: a = DSS-1, DSS-2, GSC, Vehrenberg's photographic surveys remeasured by us; b = Asiago 67/92-cm Schmidt telescope archival plates; c = Allen (1982); d = Munari & Buson (1994); e = derived from covolution with band transmission profiles of the fluxed spectra in Gutiérrez-Moreno et al. (1997); f = similarly for Munari & Zwitter (2002) spectra; g = 2MASS; h = TMM; i = photometry with the USNO 1-m telescope; l = DENIS.

	U	B	V	R_C	I_C	K	$J-H$	$H-K$	Source
1954-04-26				10.8					a
1954-07-01		14.0							a
1969-07-14		13.3							b
1969-07-16		13.2							b
1970-04-06		14.0							a
1970-06-02		14.4			11.0				b
1970-07-01		13.8			10.9				b
~1981						7.58	0.98	0.34	c
1982-03-22		13.0							a
1987-06-29			12.5						a
1990-06-24	12.72	13.73	12.94	11.82	10.82				d
1990-03-16						7.66	1.06	0.31	d
1991-07-01	12.6	13.7	12.9	11.6	10.8				e
1992-03-09				11.7					a
1993-07-27		14.1	13.1	12.0					f
1996-06-16			12.7						a
1998-04-23						7.48	0.87	0.41	g
1999-06-08			10.5						h
2000-04-30	10.97	11.82	11.32	10.65	10.03				i
2000-05-02	11.00	11.91	11.36	10.74	10.07				i
2000-05-28	11.08	11.90	11.38	10.70	10.09				i
2000-10-10					10.11	7.50			l
2004-07-16	13.15	13.84	13.09	11.72	10.72				i
2004-08-04	13.22	13.91	13.14	11.74	10.74	7.56	0.94	0.36	i

the observations, which largely increased the optical brightness of the WD. Direct evidence for accretion discs is missing, given their low luminosity compared with the glare of the circumstellar nebular material and the brightness of the central star (especially if burning hydrogen at the surface). Indirect suggestions for the presence of discs are generally based on the interpretation of the flickering so far detected in ~20 per cent of surveyed symbiotic stars, e.g. CH Cyg (Sokoloski & Kenyon 2003), T CrB (Zamanov et al. 2004), MWC 560 (Tomov et al. 1995; Dobrzycka, Kenyoyn & Milone 1996), RS Oph and Mira A+B (Sokoloski, Bildsten & Ho 2001), and the appearance sometimes during outbursts of secondary periodicity (at $\sim 0.9 \times P_{\rm orb}$) and light-curve shapes resembling the 'superhumps' found in cataclysmic variables (Mikolajewska et al. 2002).

In this paper we present direct evidence that, at least in the symbiotic binary Hen 3-1341, the spectroscopic appearance of bipolar jets is limited to the early and brightest outburst phases, and that the jets are fed by the wind from the outbursting component. When the wind quenches during the decline from outburst maximum, the jets also vanish, in a 1:1 correspondence.

2 CONDITIONS IN QUIESCENCE AND OUTBURST

When TMM discovered the jets in the summer of 1999 they found Hen 3-1341 at $V = 10.5$, much brighter than on the Palomar charts ($B = 14.0$), and concluded the system was undergoing an outburst. Not much else is known about the photometric and spectroscopic history of Hen 3-1341 or the reality and characteristics of the outburst itself. A proper investigation is mandatory for the obvious implications on the nature and evolution of the jets.

With the aim of recovering the photometric history of Hen 3-1341, (i) we have obtained $UBV(RI)_C$ JHK photometry of Hen 3-1341 with the United States Naval Observatory (USNO) 1.0-m and 1.5-m telescopes, (ii) we have measured the brightness on photographic plates found in the Asiago 67/92 Schmidt archive and on plates of the DSS-1, DSS-2, GSC and Vehrenberg's photographic surveys, and (iii) we have derived $UBV(RI)_C$ magnitudes from published optical spectra calibrated into absolute fluxes. These data are given in Table 1 together with values from the Two-Micron All-Sky Survey (2MASS) and the Deep Near-Infrared Southern Sky Survey (DENIS), and $UBV(RI)_C$ JHK from the symbiotic star photometric catalogues of Allen (1982) and Munari et al. (1992). These are plotted in Fig. 1, together with amateur estimates kindly provided by Albert Jones (New Zealand) and the Variable Star Network

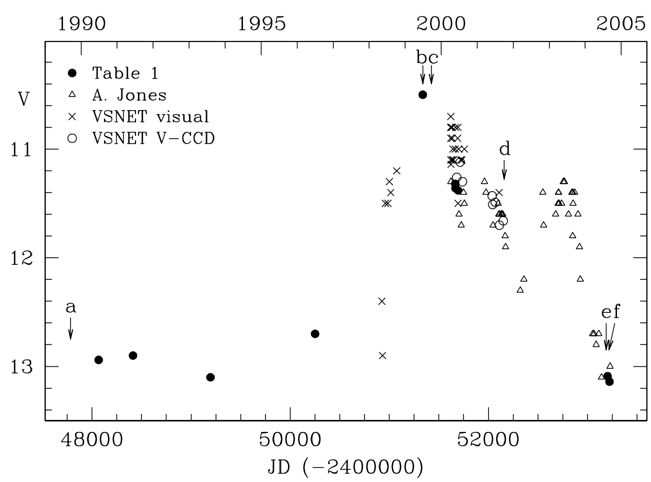

Figure 1. The V-band light curve of Hen 3-1341 over the last 15 yr showing the 1998–2004 outburst. The arrows point to the epochs of the spectra in Fig. 3.

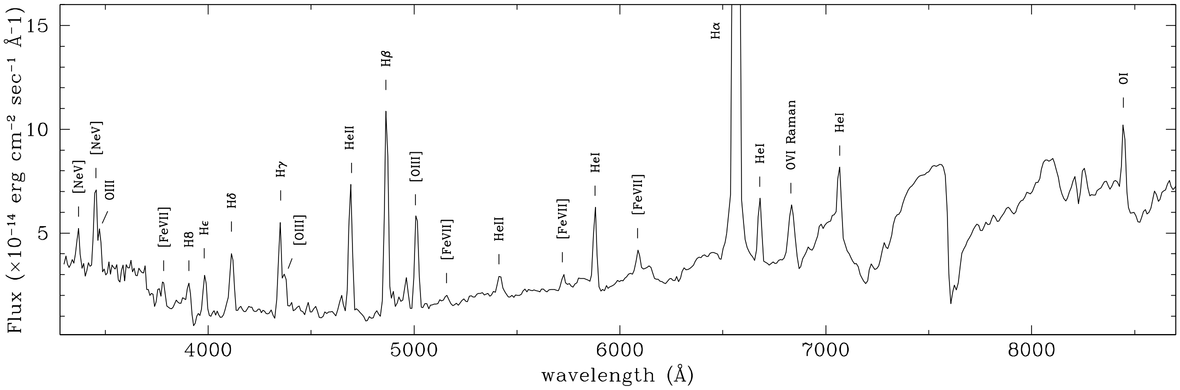

Figure 2. Low-resolution spectrum of Hen 3-1341 in quiescence on 2004 July 17.

(VSNET) organization, to document the photometric evolution over the last 15 yr.

Fig. 1 reveals that Hen 3-1341 has undergone a large outburst lasting from 1998 to 2004, characterized by a rapid rise to maximum and a complex pattern of minima and maxima during the decline phase. The outburst reached maximum V brightness right at the time TMM discovered the jet lines and found the high-ionization emission lines to have vanished and lower-energy ones somewhat weakened, while an A-type continuum dominated the spectrum, as in a typical symbiotic star outburst (cf. Ciatti 1982). The end of the outburst and return to quiescence by summer 2004 is confirmed by the spectrum in Fig. 2, which we obtained on 2004 July 17 with the B&C+CCD spectrograph of the 1.22-m telescope operated in Asiago by the Department of Astronomy of the University of Padova. The spectrum is characterized by strong emission lines of [Fe VII], [Ne V], He II and O VI (Raman scattered), identical to the 1993 pre-outburst quiescent spectrum by Munari & Zwitter (2002).

The emission-line spectrum of Hen 3-1341 in quiescence both in the optical (from Fig. 2) and in the ultraviolet (the *International Ultraviolet Explorer* spectrum of Gutiérrez-Moreno et al. 1997) has been modelled with the CLOUDY software package (see http://www.nublado.org/) to obtain round estimates of basic physical parameters, assuming a simple spherical symmetric gas distribution originating from the $\rho(r) \propto r^{-2}$ wind of the cool giant ionized by the radiation from the WD companion. We found the nebular material to be radiation bounded and to extend for ∼17 au, for a total mass of $\sim 7 \times 10^{-6}$ M$_\odot$ contained within. The gas electronic temperature and density are $T_e \sim 1 \times 10^5$ K and $N_e \sim 2 \times 10^8$ cm^{-3} close to the ionizing source, decreasing to $T_e \sim 4 \times 10^3$ K and $N_e \sim 6 \times 10^5$ cm^{-3} at the ionization boundary. The modelling supports solar metallicity and chemical partition, although with Ne and N apparently enhanced by ∼10× (which is what is expected when ejecta or wind from the outbursting WD are mixed with the circumstellar material originating from the M giant; see Nussbaumer et al. 1988; Warner 1995). The central star has $T_{\rm WD} \sim 1.2 \times 10^5$ K and $R_{\rm WD} \sim 0.14$ R$_\odot$, for a luminosity of 3.8×10^3 L$_\odot$, which are consistent with those previously found by Gutiérrez-Moreno et al. (1997). Such a quiescent luminosity cannot be sustained by pure accretion because that would require an implausibly large accretion rate of 1×10^{-6} M$_\odot$ yr^{-1} on a 0.5-M$_\odot$, WD.

The quiescent luminosity is instead well explained by stable H-burning conditions of accreted matter on the surface of the WD. Because the stably burning WD in Hen 3-1341 does not expand to large dimensions during quiescence, the accretion rate must match the burning rate, or $\dot{M}_{\rm H} \sim 5 \times 10^{-8}M_\odot$ yr^{-1}, which is in line with the expected accretion rate for symbiotic stars (see Kenyon & Webbink 1984). From Iben & Tutukov (1989) numerical simulations, $T_{\rm WD} \sim 1 \times 10^5$ K and $R_{\rm WD} \sim 0.1$ R$_\odot$ correspond to a stable H-burning 0.4-M$_\odot$ WD. From Table 1 it is evident that the WD in Hen 3-1341 has been in that state since at least the time of the first Palomar survey, 50 yr ago. This is in line with the theoretical expectations for a 0.4-M$_\odot$ H-burning WD, which predicts an 'on' period of ∼5000 yr, or 10 times shorter if the mass of the envelope is reduced by a wind (Iben 2003).

To gain physical insight into the optical 1998–2004 outburst, we have integrated the energy between the outburst light curve in Fig. 1 and the $V \sim 13.1$ reference value for quiescence, to derive the total radiated energy. The colour evolution of the outbursting component is missing for lack of multiband simultaneous observations. Colour information is available (see Table 1) only for the three observations in 2000, when the outbursting component was roughly mid-way between outburst maximum and quiescence. For sake of discussion, the corresponding B–$V = 0.52$ is taken to represent the average colour of the outbursting component. To estimate the reddening we have measured the equivalent width of interstellar Na I and K I absorption lines in high-resolution spectra of Hen 3-1341 that we have secured with the ELODIE spectrograph at the Observatoire de Haute-Provence (OHP) and the Echelle spectrograph at the 1.82-m telescope operated in Asiago by the Italian National Institute of Astrophysics (INAF). Following the calibration of Munari & Zwitter (1997), the reddening is found to be $E(B$–$V) = 0.47$ and therefore the intrinsic average colour for the outbursting component is $(B$–$V)_\circ = 0.05$. The corresponding bolometric correction is −0.10 according to Bessell, Castelli & Plez (1998) and the spectral type is A2 following Fitzgerald (1970). Adopting the distance of 3.1 kpc derived by Gutiérrez-Moreno et al. (1997), the total energy radiated by the outburst turns out to be $\sim 6 \times 10^{44}$ erg (it is worth noting that this value refers solely to the outburst stellar continuum; any other amount going into energetic tails that keep alive some ionization of the circumstellar gas would add to this.) The $\sim 6 \times 10^{44}$ erg would correspond to the potential energy released by the accretion on to a 0.5-M$_\odot$ WD of $\sim 4 \times 10^{-6}$ M$_\odot$ (at a mean rate of $\sim 1 \times 10^{-6}$ M$_\odot$ yr^{-1}), which is implausibly large. In fact, it is orders of magnitude larger than the typical mass dumped through an accretion disc during outbursts in cataclysmic variables (Warner 1995), and the required mass loss from the donor star would be orders of magnitude larger than expected for the M2 III non-variable companion, which did not experience any major instability at the time of outburst onset (see stable infrared magnitudes in Table 1).

The 6×10^{44} erg radiated during the outburst instead corresponds to the nuclear burning of $\sim 5 \times 10^{-8}$ M$_\odot$ of hydrogen, at an average rate of $\sim 1 \times 10^{-8}$ M$_\odot$ yr^{-1} or $\sim 1 \times 10^3$ L$_\odot$. This corresponds to about ∼1/4 of the luminosity in quiescence. This suggests that the 1998–2004 event, which we previously called an 'outburst', was actually a partial reprocessing into the optical of the radiation flowing into the far-ultraviolet during 'quiescence'. In fact, strong hydrogen and He I emission lines remained always visible, in spite of a recombination time of the order of $t_{\rm rec} \sim 1/(n_{\rm s}\,\alpha_{\rm B}) \sim 2$ months, even at the outer boundary of the ionized gas region, indicating that not all ultraviolet radiation was suppressed. The reprocessing took place in the envelope of the WD that expanded and cooled to $T_{\rm eff} \sim 1 \times 10^4$ K and $R \sim 20$ R$_\odot$. The width of the stable H-burning strip in the $M_{\rm WD}$, $\dot{M}_{\rm acc,WD}$ plane is a narrow one, and minimal increases in $\dot{M}_{\rm acc,WD}$ triggers an expansion and consequent cooling of the WD envelope (see Iben 2003). We are therefore led to interpret the 1998–2004 'outburst' as having been caused by a temporary (and marginal) increase in the mass loss from the M2 III that gave no appreciable signal in the infrared photometry of Table 1 but caused $\dot{M}_{\rm acc,WD}$ to rise above the narrow equilibrium strip. The surplus accreted material was partially burned and partially carried away by the fast wind traced by the P Cyg profiles of He I lines in Fig. 3. When the WD envelope mass returned to the equilibrium value, the envelope retraced to small radius and high temperature and Hen 3-1341 resumed the photometric and spectroscopic 'quiescent' appearance.

3 EVOLUTION OF THE JETS AND THEIR FEEDING MECHANISM

Following the discovery of bipolar jets by TMM in 1999 June, we reobserved Hen 3-1341 at high spectral resolution at later dates. The results for Hα and He I 5876-Å profiles are shown in Fig. 3 together with the original TMM discovery spectrum and a pre-outburst spectrum obtained at the European Southern Observatory (ESO) by van Winckel, Duerbeck & Schwarz (1993). From Fig. 3 it is evident how the blueshifted and redshifted emission components due to the bipolar jets were absent in the quiescence before as well as after the outburst, and were strongest at peak outburst optical brightness, declining in strength with the outburst retracing from maximum. It is worth noticing the similarity between the terminal wind velocity ($\sim$770 km s^{-1}) and jet projected velocity ($|\Delta R\, {\rm V}_\odot| \sim 820$ km s^{-1}) at the time of onset of the jets (1999 June), which is best appreciated in the left insert of the bottom panel of fig. 1 of TMM. A most interesting comparison is between the strength of optical jet lines and the amount of mass loss by wind from the WD as traced by the P Cyg profiles of He I lines in Fig. 3. The correlation is a very tight one. The jets were most prominent when the wind was strongest, and declined in parallel with the decrease of wind intensity. To our knowledge, this evidence is among the most direct and convincing proof of the 'energy/wind source associated with the central accreting object' postulated by the Livio (1997) mechanism of jet production. Given the association between jet appearance and outburst states also for other objects (e.g. CH Cyg, Z And, StHα-190 and MWC 560), the symbiotic stars as a class support the energy/wind source hypothesis. We suggest that the spectroscopic search for jets in symbiotic stars could pay higher dividends if focused on the outburst phases characterized by maximum wind intensity.

From the integrated flux of the jet features in the Hα spectrum at outburst maximum in Fig. 3 (1999 June 8), and assuming that all the hydrogen within the jets is ionized and that the jets are optically thin in Hα, a total mass in the jets of $M_{\rm jet} \sim 2.5 \times 10^{-7}$ M$_\odot$ is derived. This amount would rise in the presence of neutral gas or optically thick conditions. The kinetic energy deposited in the jets corresponding to the observed 820 km s^{-1} projected velocity is therefore $E^{\rm kin}_{\rm jet} \sim 1.7 \times 10^{42}$ $(\sin i)^{-1}$ erg, where i is the unknown

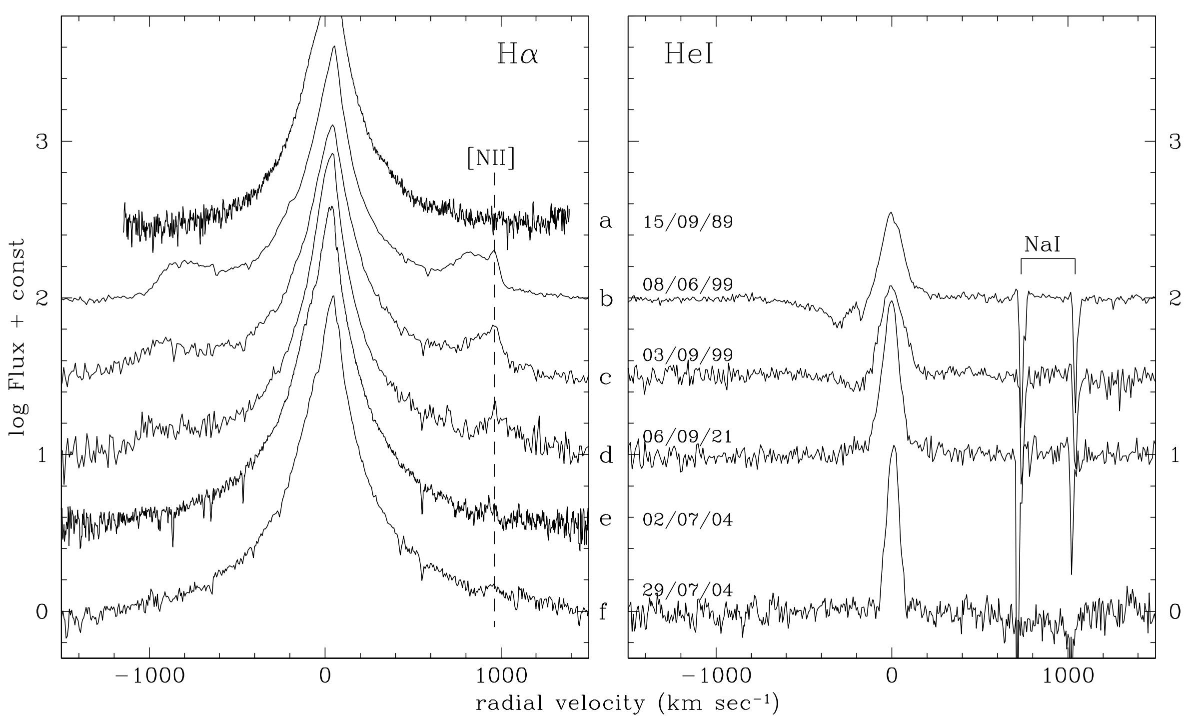

Figure 3. Evolution of Hα and He I 5876-Å profiles between 1989 and 2004. The profiles are plotted on a logarithmic flux scale to emphasize visibility of the jets in Hα and the wind absorption signatures in He I. (a) From van Winckel et al. (1993); (b), (c), (d), (f) Echelle spectrograph at the Asiago 1.82-m telescope; (e) ELODIE spectrograph at the OHP 1.93-m telescope.

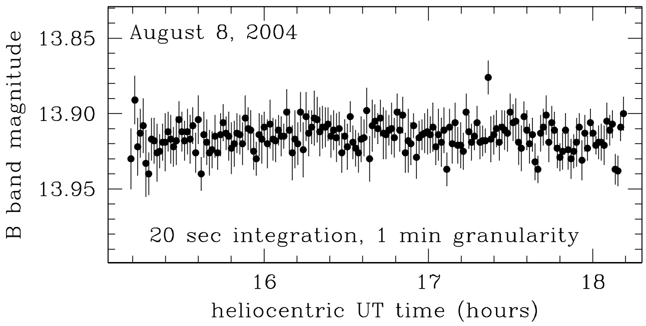

Figure 4. Time-resolved monitoring of Hen 3-1341 in the *B* band on 2004 August 8 with the USNO 1-m telescope, looking for flickering and signature of rotation of a magnetic WD.

orbital inclination. This corresponds to $\sim 0.3(\sin i)^{-1}$ per cent of the total energy radiated during the outburst.

Fig. 3 suggests a small increase with time in the observed velocity separation of the jets, amounting to $|\Delta R\, V_{\odot}| \sim 820$ km s^{-1} in 1999 June, 910 km s^{-1} in 1999 September and 1000 km s^{-1} in 2001 September. Different explanations could be invoked – including a variable projection angle of the jet axis on the line of sight as caused by a precession motion – but there are not enough data to decide in favour of any of them.

Finally, we have also searched for a signature of rotation of a magnetic WD in Hen 3-1341 by looking for coherent modulation in time-resolved *B*-band photometry that we secured in 2004 with the USNO 1.0-m telescope (see Fig. 4). None was found with an amplitude in excess of 0.004 mag, but this was an expected result, because with the system in quiescence the circumstellar nebular emission is enormously brighter than the WD in the *B* band. A more profitable search will have to wait for the next outburst state of Hen 3-1341.

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